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(12) **United States Patent**
Hsieh et al.

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(54) **PHOTOVOLTAIC SYSTEM HAVING
POWER-INCREMENT-AIDED
INCREMENTAL-CONDUCTANCE
MAXIMUM POWER POINT TRACKING
CONTROLLER USING
CONSTANT-FREQUENCY AND
VARIABLE-DUTY CONTROL AND METHOD
THEREOF**

USPC 307/151
See application file for complete search history.

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(57) **ABSTRACT**

The configurations of photovoltaic system and methods thereof are provided. The proposed photovoltaic system includes a PI-INC MPPT controller using a constant-frequency variable-duty (CFVD) control and guided by an I_{pv} - V_{pv} curve and a P_{pv} - V_{pv} curve.

7 Claims, 11 Drawing Sheets

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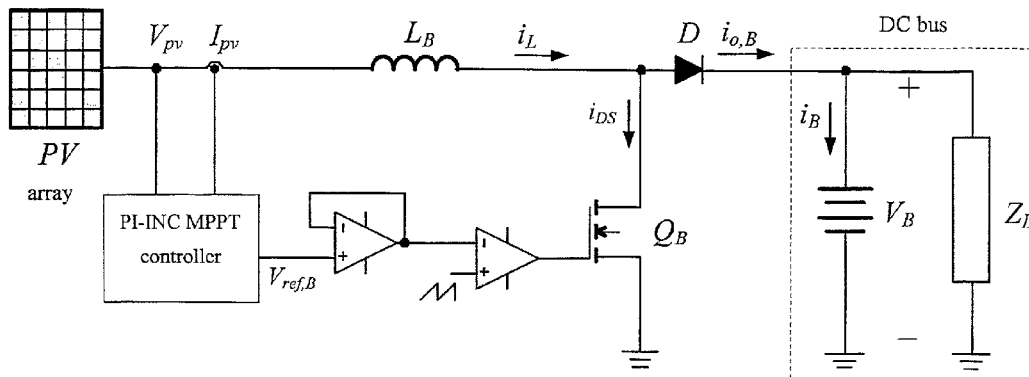
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H02J 3/38 (2006.01)
H02J 7/35 (2006.01)

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CPC **H02J 3/385** (2013.01); **H02J 7/35**
(2013.01); **Y02E 10/566** (2013.01); **Y02E 10/58** (2013.01); **Y10T 307/50** (2015.04)

(58) **Field of Classification Search**
CPC H02J 3/385; H02J 7/35; Y02E 10/58;
Y02E 10/566



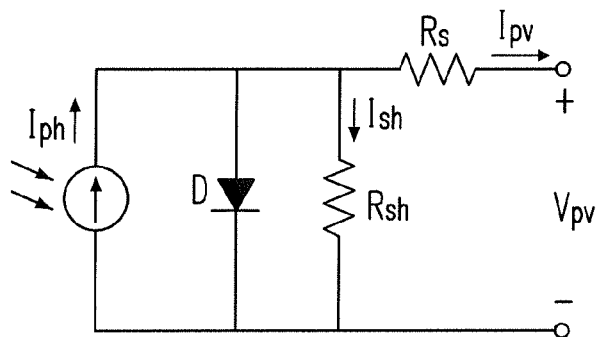


Fig. 1(a)(Prior Art)

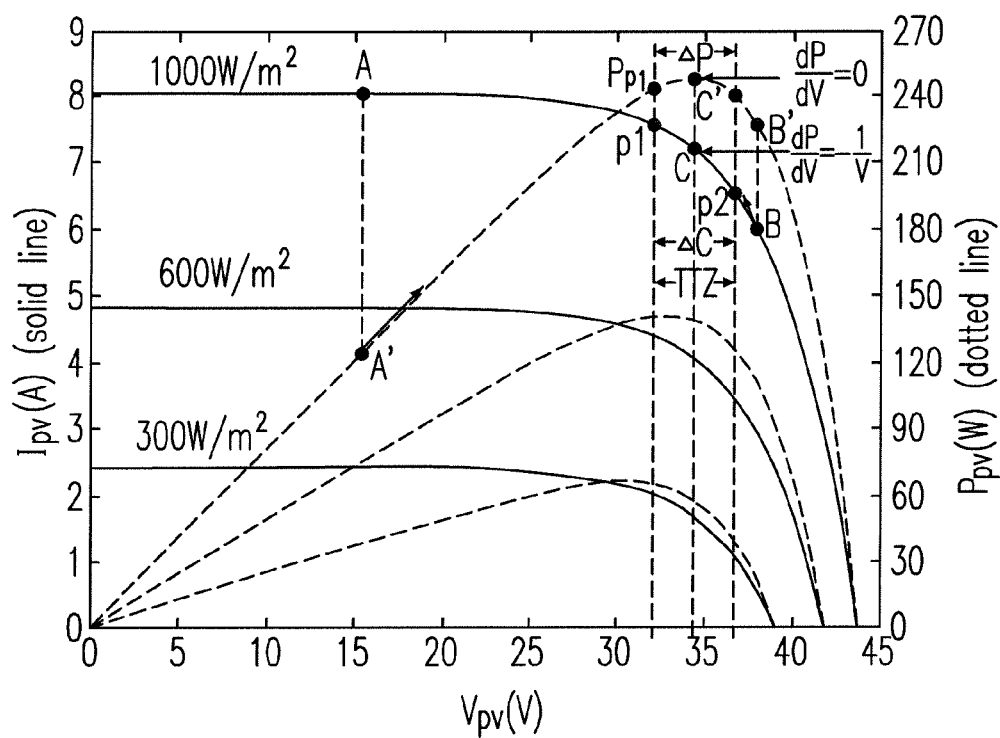


Fig. 1(b)

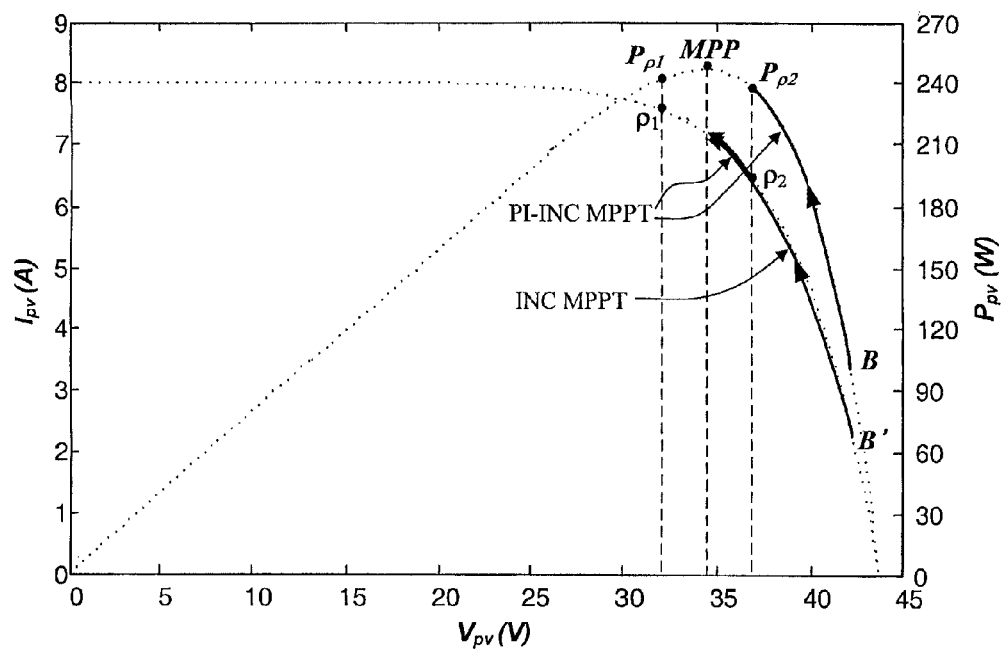


Fig. 2(a)

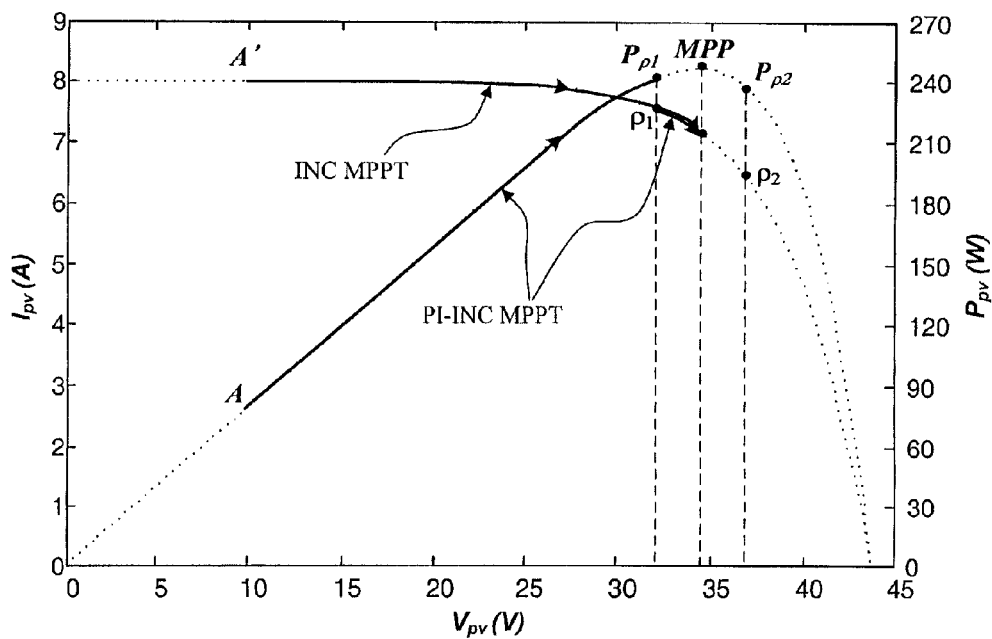


Fig. 2(b)

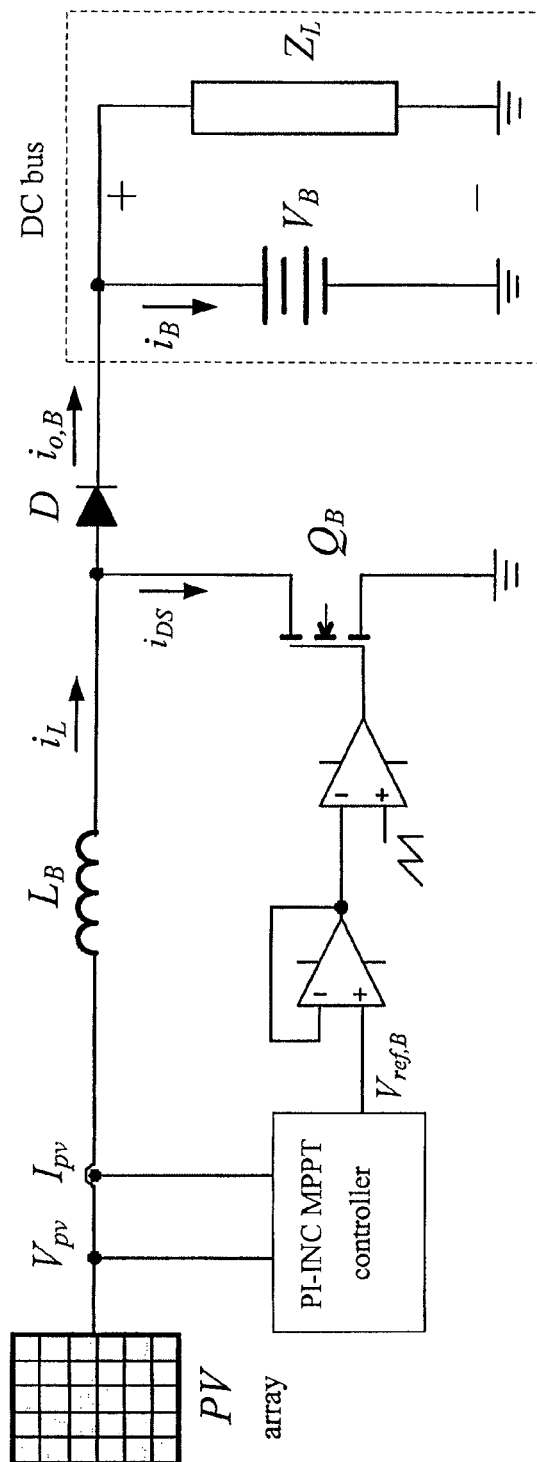


Fig. 3(a)

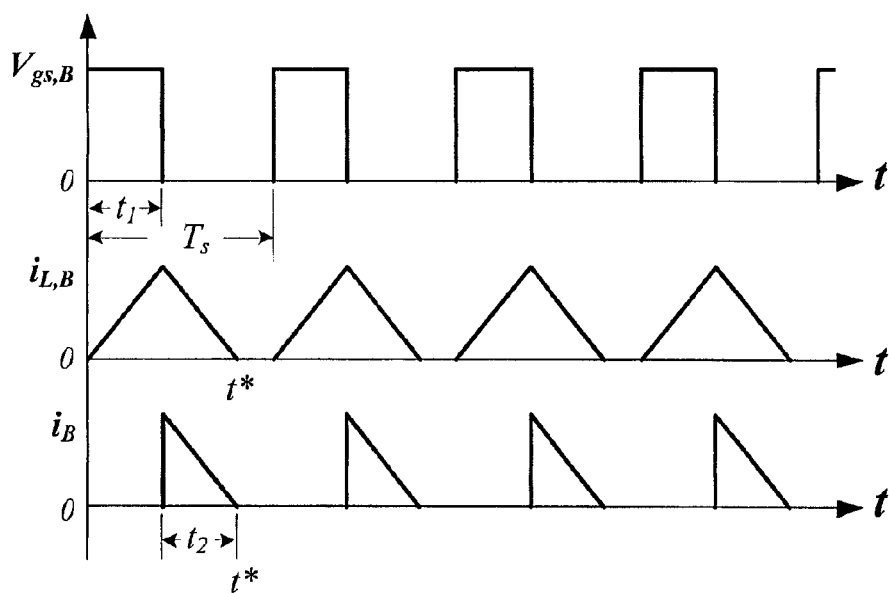


Fig. 3(b)

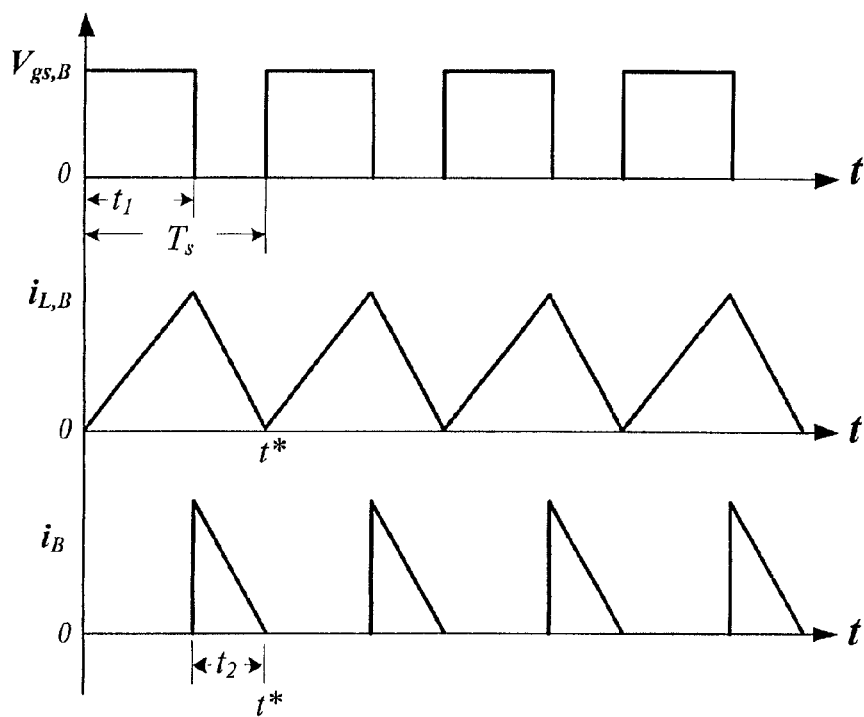


Fig. 3(c)

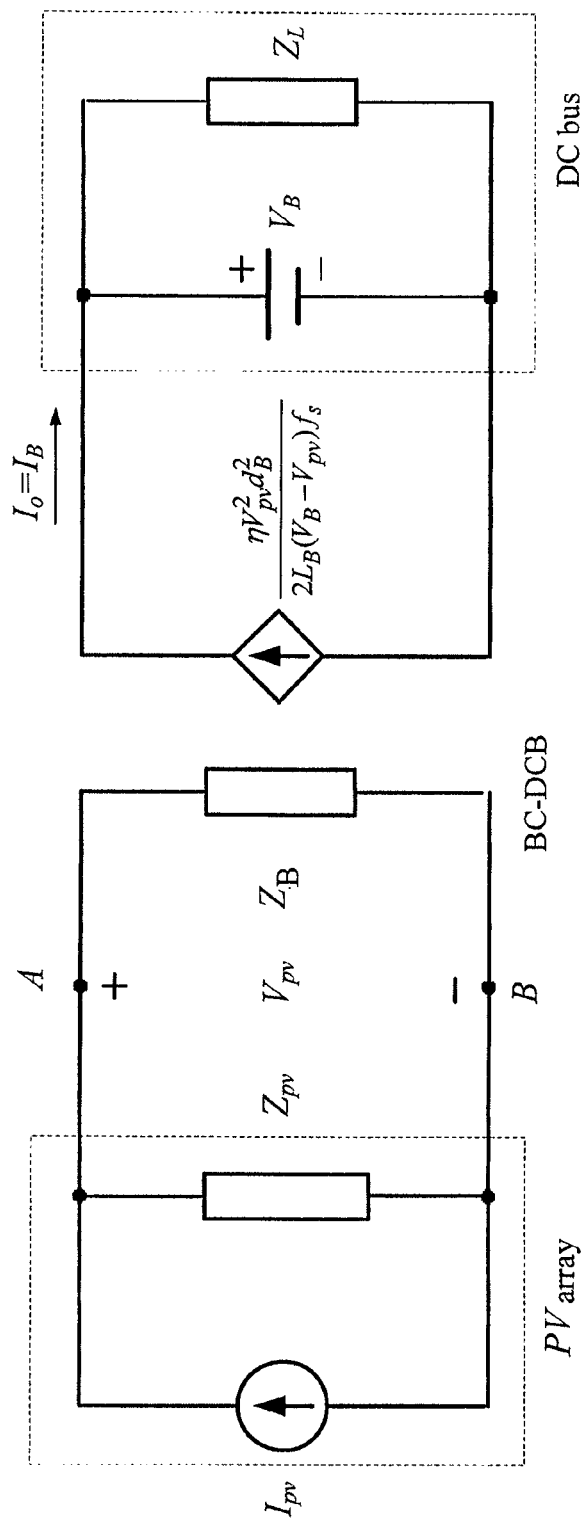


Fig. 3(d)

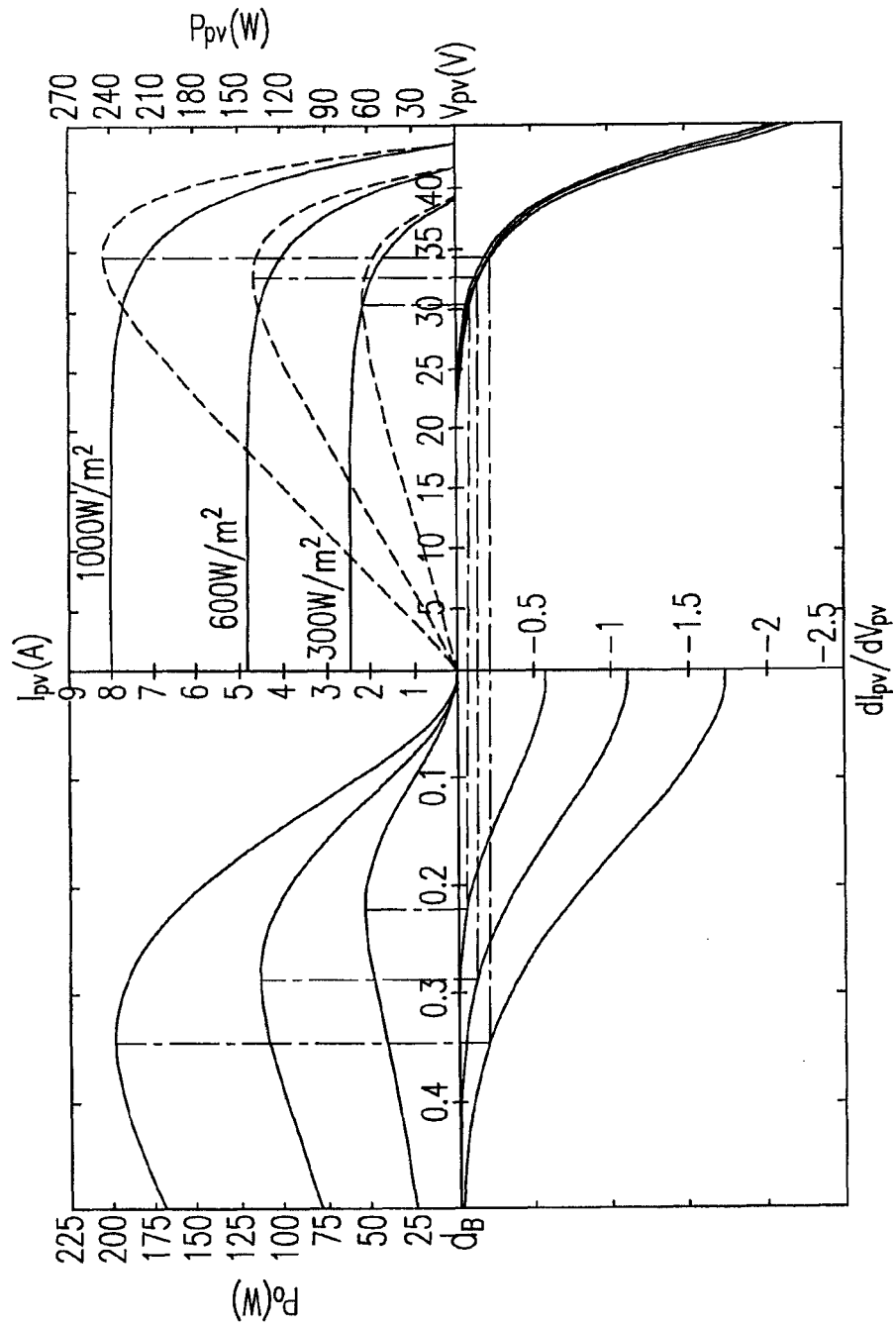


Fig. 4

Main Program

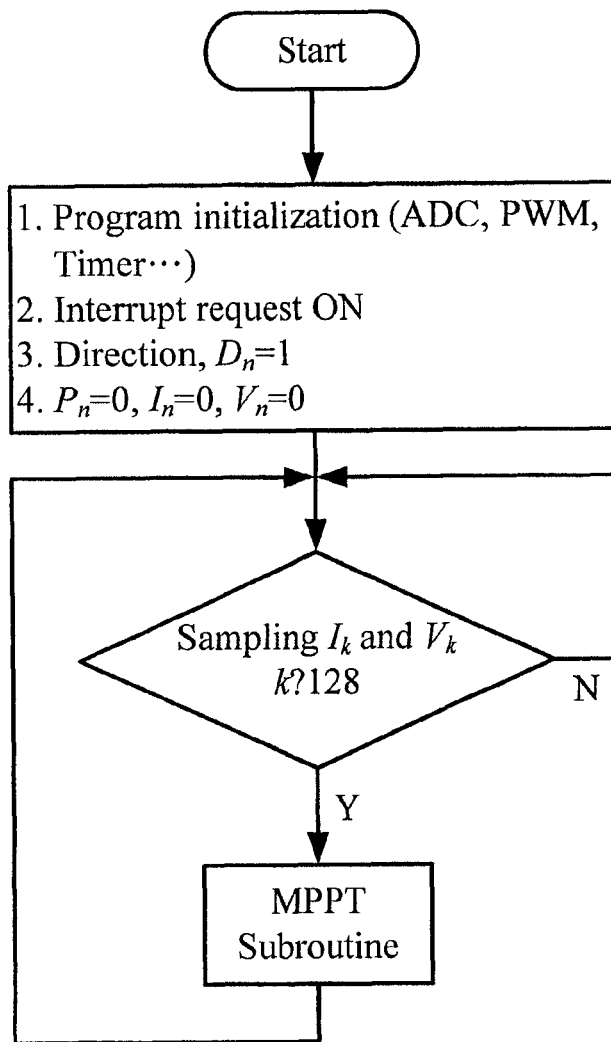


Fig. 5(a)

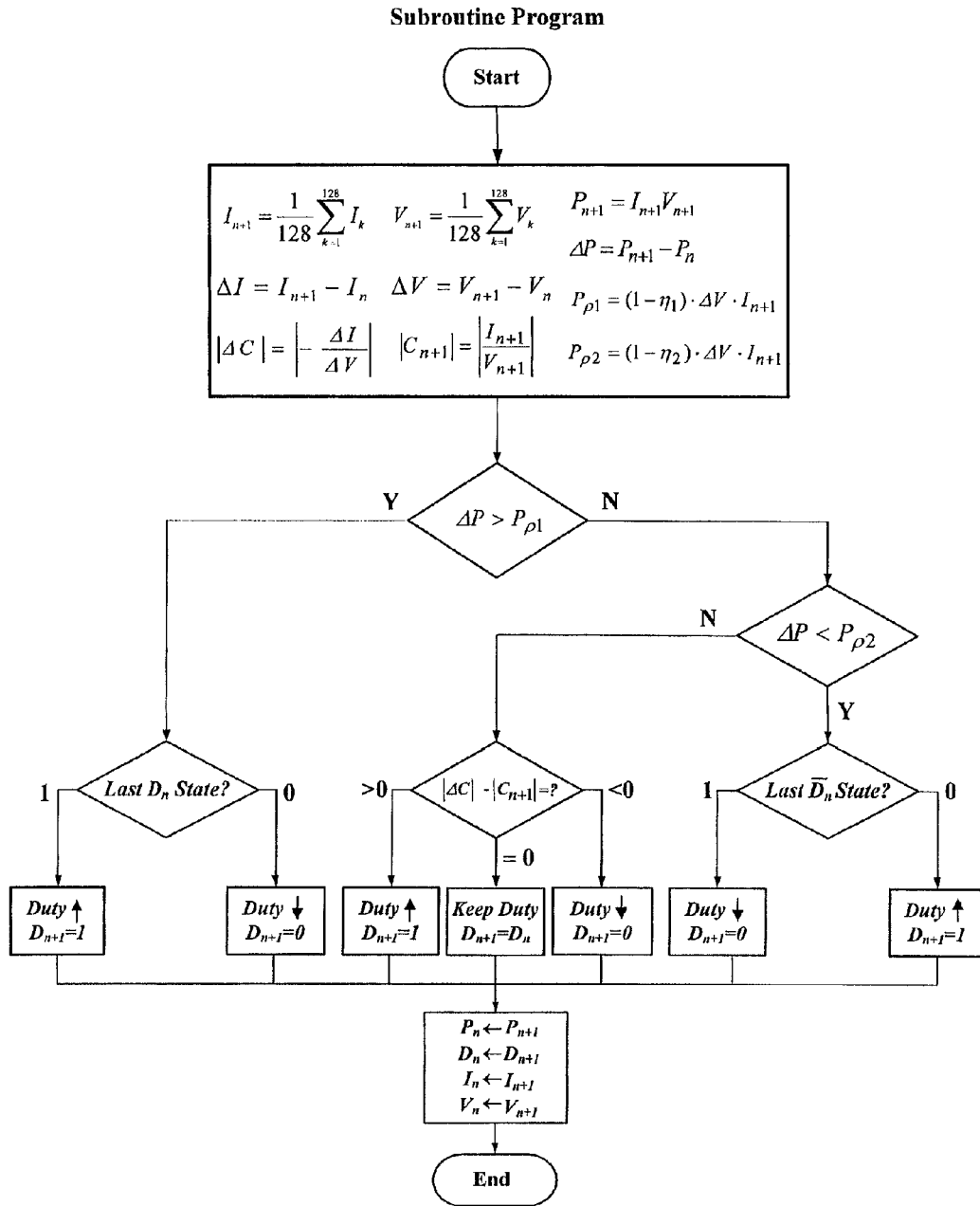


Fig. 5(b)

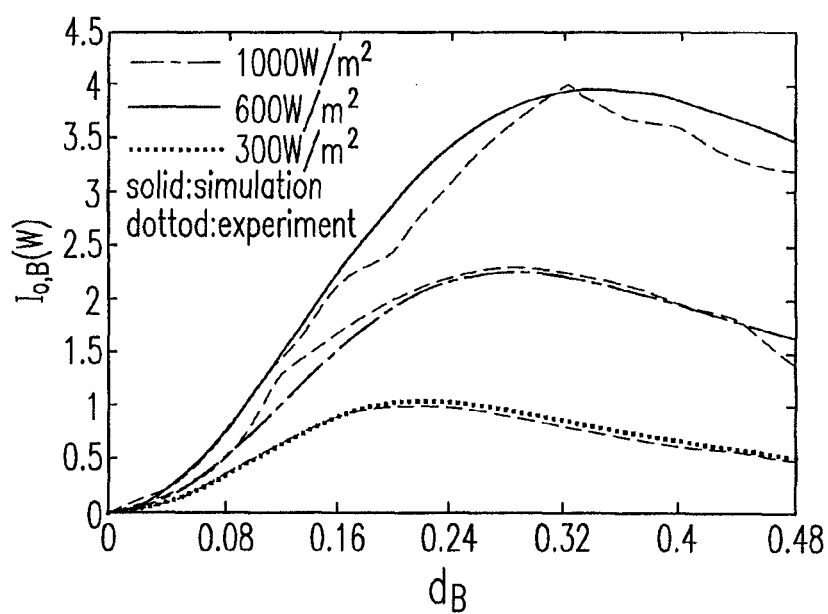


Fig. 6(a)

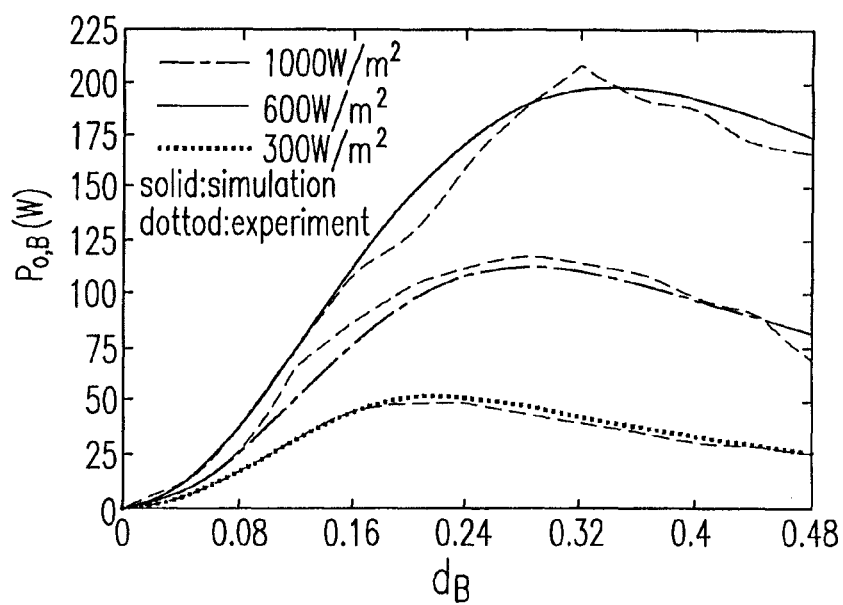


Fig. 6(b)

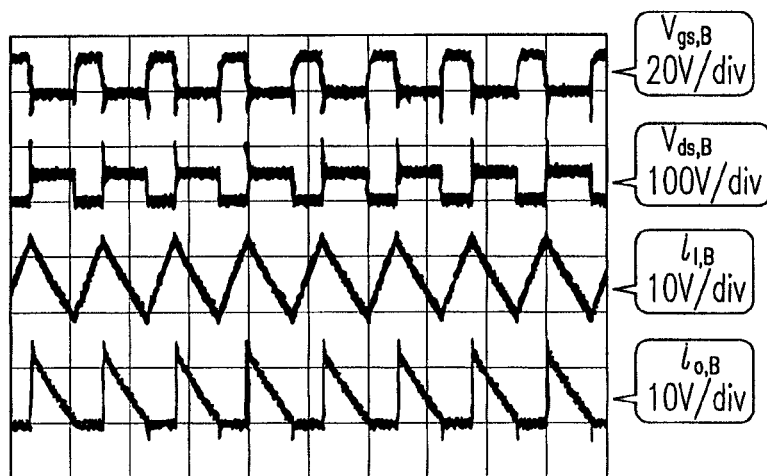


Fig. 7

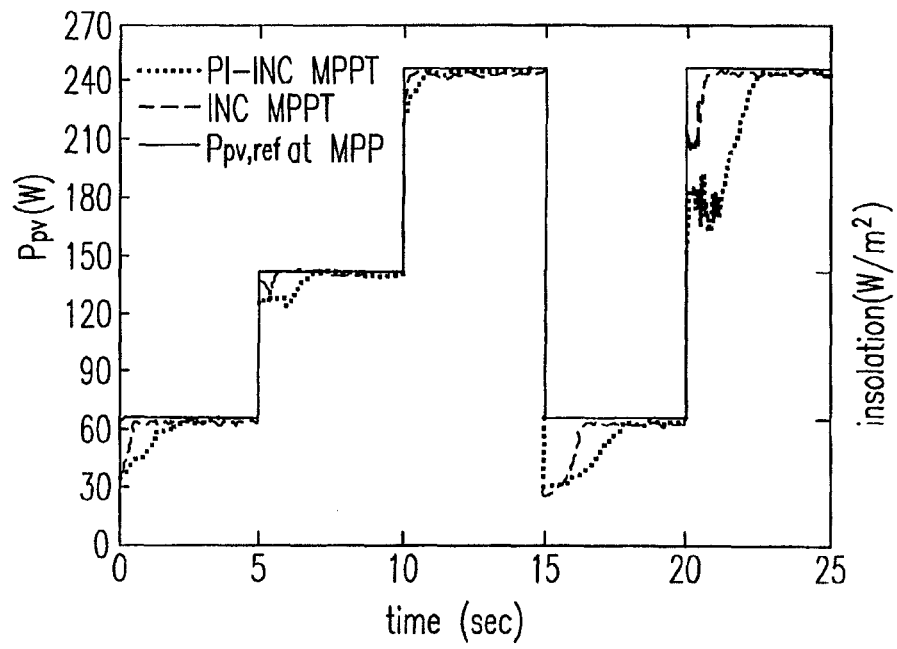


Fig. 8

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PHOTOVOLTAIC SYSTEM HAVING POWER-INCREMENT-AIDED INCREMENTAL-CONDUCTANCE MAXIMUM POWER POINT TRACKING CONTROLLER USING CONSTANT-FREQUENCY AND VARIABLE-DUTY CONTROL AND METHOD THEREOF

CROSS-REFERENCES TO RELATED APPLICATIONS

The application claims the benefit of Taiwan Patent Application No. 101109929, filed on Mar. 22, 2012, in the Taiwan Intellectual Property Office, the disclosures of which are incorporated herein in their entirety by reference.

FIELD OF THE INVENTION

The present invention relates to a photovoltaic (PV) system having a power-increment-aided incremental-conductance (PI-INC) maximum power point tracking (MPPT) controller. In particular, it relates to the photovoltaic system having the PI-INC MPPT controller using a constant-frequency variable-duty control.

BACKGROUND OF THE INVENTION

FIG. 1(a) shows a circuit diagram of an equivalent circuit of a typical solar cell unit, wherein D is an LED, Rsh is a parallel-connected inner resistor, Rs is a series-connected inner resistor, and Iph is an output current of the solar cell unit. There are six well-known solar energy MPPT techniques including voltage feedback method, power feedback method, practical measurement method, linear approximation method, perturbation and observation method and incremental conductance method.

In these six methods, the perturbation and observation method is the most widely used one. This method uses the perturbation to measure the new output voltage and current of the two sides of the solar panel, calculate its power, and compare with the power sampled last time to get its change amount. If the new power value is higher than the power value of last time, it represents that the perturbation direction is correct. Otherwise, the direction of perturbation shall be reversed. And, the next movement of adding or subtracting the perturbation is decided accordingly. Since the procedure of perturbation will constantly change the output power of the solar panel (or the PV array), the last operating point would be stabilized within a small range around the maximum power point (MPP). The drawback of this method is that the procedure of perturbation will never be ceased, which will cause oscillation around the MPP, result in the energy loss and decrease the efficiency of conversion.

The incremental conductance method is applied via a principle that a rate of change of an output power with respect to a voltage of a solar panel is zero at an MPPT, and at a place corresponding to $dP/dV=0$ on the current-voltage characteristic curve, e.g. as shown in FIG. 1(b), and the incremental conductance method directly finds out

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V},$$

(1)

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where I is a solar cell current, V is a solar cell voltage, ΔV is a voltage increment, and ΔI is a current increment. Via measuring a conductance value of $\Delta I/\Delta V$ and compared it with an instantaneous conductance of $-I/V$ of the solar panel to judge whether $\Delta I/\Delta V$ is larger than, smaller than, or equivalent to $-I/V$ so as to determine whether the next incremental change should be continued. When the incremental conductance conforms to formula (1), the solar panel is for sure to be operated at a maximum power point (MPP), and there will be no more next increment. This method engages in a tracking via the modification of the logic expression, there is not any oscillation around the MPP such that it is more suitable to the constantly changing conditions of the atmosphere. The incremental conductance method can accomplish the MPPT more accurately and decrease the oscillation problem as in the perturbation and observation method, but it still has some drawbacks. As shown in FIG. 1(b), using the curve of insolation 1000 W/m² as an example, if it is detected at the very beginning that the solar panel is working at point A on the I_{pv}-V_{pv} curve, that is at the left-hand side of point C (the MPP), and corresponding to point A' on the P_{pv}-V_{pv} curve, the (photovoltaic) system will cause the solar panel to move its operating point from A to its right-hand side and track towards the point C. On the contrary, if it is detected that the solar panel is working at point B on the I_{pv}-V_{pv} curve, that is at the right-hand side of point C (the MPP), and corresponding to point B' on the P_{pv}-V_{pv} curve, then the system will cause the solar panel to move its operating point from B to its left-hand side and track towards the point C. Finally, when the detected conductance value of $\Delta I/\Delta V$ satisfies formula (1), the system will keep the operating point of the solar panel at point C of the I_{pv}-V_{pv} curve and at point C' of the P_{pv}-V_{pv} curve to maintain the maximum power output of the solar panel. However, the drawbacks of the incremental conductance method are that at the left-hand side of point C (the MPP) of the I_{pv}-V_{pv} curve, it is found that the change of current with respect to voltage is almost a constant value in most of the sections, and is approximately equal to the short-circuit current, and at the right-hand side of point C, the problem is the change of voltage with respect to current is not obvious. In other words, at the left-hand side of point C, the change of current with respect to voltage is relatively insensitive and has a poor responsibility. On the contrary, at the right-hand side of point C, the change of voltage with respect to current is relatively insensitive. However, the best tracking range of the incremental conductance method is in the area around point C, where the changes of current and voltage are relatively obvious, and it has a superior responsibility. But, on the left-hand side and the right-hand side of point C, there are respectively drawbacks of the change of current with respect to voltage is relatively insensitive and the change of voltage with respect to current is relatively insensitive such that result in the incremental conductance method could not give full scope of its function and there are phenomena of tardiness and slow response speed when engaged in the MPPT, which will influence the output efficiency of the maximum power.

Keeping the drawbacks of the prior arts in mind, and employing experiments and research full-heartily and persistently, the applicant finally conceived a photovoltaic system having a power-increment-aided incremental-conductance maximum power point tracking controller using a constant-frequency variable-duty control and method thereof.

SUMMARY OF THE INVENTION

It is a primary objective of the present invention to provide a photovoltaic system having a power-increment-

aided incremental-conductance maximum power point tracking controller using a constant-frequency variable-duty control. This technique includes PI-MPPT and INC-MPPT, and sets up a threshold tracking zone in the area with obvious changes on the I_{pv} - V_{pv} curve around point C. If the power increment falls into the threshold tracking zone, the system enters the INC fine tracking and uses the I_{pv} - V_{pv} curve as a tracking standard. On the contrary, if the power increment falls outside the threshold tracking zone, the system enters the PI coarse tracking and uses the P_{pv} - V_{pv} curve as a tracking standard. The proposed photovoltaic system has a relatively quick response and a relatively better output efficiency of the maximum power when engaged in the MPPT.

According to the first aspect of the present invention, a photovoltaic system with a photovoltaic current (I_{pv}), a photovoltaic voltage (V_{pv}), a photovoltaic power (P_{pv}), a duty cycle (d_B) and an output power (P_o), wherein there is a derivative (dI_{pv}/dV_{pv}) of I_{pv} with respect to V_{pv} including a power-increment-aided incremental-conductance (PI-INC) maximum power point tracking (MPPT) controller guided by a control chart, wherein the control chart includes, an I_{pv} - V_{pv} curve and a P_{pv} - V_{pv} curve, a dI_{pv}/dV_{pv} - V_{pv} curve, a dI_{pv}/dV_{pv} - d_B curve, and a P_o - d_B curve.

According to the second aspect of the present invention, a photovoltaic system includes a controller having a power-increment (PI) module to be used to determine whether a specific conductance derivative ratio enters a threshold tracking zone.

According to the third aspect of the present invention, a method for operating a controller of a photovoltaic system includes a step of: providing a power-increment (PI) module to be used to determine whether a specific conductance derivative ratio enters a threshold tracking zone.

The present invention can be best understood through the following descriptions with reference to the accompanying drawings, in which:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1(a) shows a circuit diagram of an equivalent circuit of a typical solar cell unit;

FIG. 1(b) shows a waveform diagram with I_{pv} - V_{pv} and P_{pv} - V_{pv} curves having designated threshold tracking zones;

FIGS. 2(a)-2(b) respectively show a waveform diagram of the various tracking routes of the PI-INC MPPT method proposed by the present invention and the INC MPPT method when they are fallen on the right-hand side and the left-hand side of the MPP;

FIG. 3(a) shows a circuit diagram of a photovoltaic DC link converter according to the preferred embodiment of the present invention;

FIG. 3(b) shows a waveform diagram of dynamic states of boost current converter (BCC) in discontinuous conduction mode (DCM) at some low insolation of the photovoltaic DC link converter as shown in FIG. 3(a);

FIG. 3(c) shows a waveform diagram of dynamic states of BCC in boundary conduction mode (BCM) at some high insolation of the photovoltaic DC link converter as shown in FIG. 3(a);

FIG. 3(d) shows an equivalent circuit diagram of the control-to-output model drawing energy from the PV array of the photovoltaic DC link converter as shown in FIG. 3(a);

FIG. 4 shows a waveform diagram of control chart of the controller of the photovoltaic DC link converter according to the preferred embodiment of the present invention;

FIG. 5(a) shows a flow chart of main program of an algorithm of PI-INC MPPT using constant-frequency variable-duty (CFVD) according to the preferred embodiment of the present invention;

FIG. 5(b) shows a flow chart of subroutine of an algorithm of PI-INC MPPT using CFVD according to the preferred embodiment of the present invention;

FIGS. 6(a)-(b) respectively show a waveform diagram of output current versus duty ratio and output power versus duty ratio under various solar insulations of the proposed photovoltaic DC link converter using CFVD;

FIG. 7 shows a waveform diagram of the dynamic states of BCC for DC bus survived with battery of 48V at solar insolation of 1000 W/m²; and

FIG. 8 shows waveform diagram comparing PI-INC MPPT and INC-MPPT in terms of dynamic tracking behavior for various insolation changes.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Although the following description contains many specifications for the purposes of illustration, anyone of ordinary skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Accordingly, the following preferred embodiment of the invention is set forth without any loss of generality to and without imposing limitations upon, the claimed invention.

Due to the aforementioned drawbacks of the prior art, the present invention provides a PI-INC MPPT technique, this technique consists of PI-MPPT and INC-MPPT, the PI-MPPT is named as coarse-tracking and the INC-MPPT is named as fine-tracking. This motivation results from the observation of the power curve P_{pv} - V_{pv} as shown in FIG. 1(b). At the two sides of the MPP C', the changes of the power are in direct proportion to the voltage, and there is no such problems of tardiness and insensitive response area as those on the I_{pv} - V_{pv} curve. Thus, the proposed method of the present invention preserves the unique advantage of accurately tracking around the MPP C of the incremental conductance method, that is to set up the threshold tracking zone (TTZ) in the area having obvious changes on the I_{pv} - V_{pv} curve around point C as shown in FIG. 1(b), which is equivalent to define the points (ρ_1 , ρ_2) on the I_{pv} - V_{pv} curve as a conductance threshold zone (CTZ= ΔC), or corresponding to define points (P_{ρ_1} , P_{ρ_2}) on the P_{pv} - V_{pv} curve as a power threshold zone (PTZ= ΔP). The principles of this technique are that the system detects the power P_{n+1} generated by the new output voltage and the new output current of the two sides of the solar panel, and P_{n+1} is compared with the previously sampled power P_n , that is the power increment $\Delta P = P_{n+1} - P_n$. If the power increment ΔP falls into the range of threshold (P_{ρ_1} , P_{ρ_2}), the system will immediately enter the fine-tracking of the incremental conductance, and use the I_{pv} - V_{pv} curve as the tracking standard. On the contrary, if the power increment ΔP falls outside the range of threshold (P_{ρ_1} , P_{ρ_2}), the system will immediately enter the coarse-tracking of the power increment, and use the P_{pv} - V_{pv} curve as the tracking standard. Using FIG. 1(b) as an example to describe the MPPT of the present invention, for example, if the detected voltage and current, and the computed power at certain moment respectively fall on point A of I_{pv} - V_{pv} curve, and point A' of the P_{pv} - V_{pv} curve, and the computed power increment $\Delta P = P_{n+1} - P_n$ falls outside the range of threshold (P_{ρ_1} , P_{ρ_2}), the system will immediately employ the power increment tracking and use the P_{pv} - V_{pv}

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curve as a tracking standard so as to drive the point A' to be moved to point C' rapidly and to track until the power threshold point $P_{\rho 1}$. Correspondingly, the point A on the I_{pv} - V_{pv} curve is moved to C during this period and is tracked until the threshold point $\rho 1$. The tracking function of the power increment principle in this area is relatively sensitive and definite than that of the conventional incremental conductance principle. Similarly, if the detected voltage and current, and the computed power respectively fall on point B of I_{pv} - V_{pv} curve, and point B' of the P_{pv} - V_{pv} curve, as aforementioned, the same power increment tracking principle will be employed to engage in the tracking phenomenon. If the detected voltage and current, and the computed power respectively fall in the range of threshold ($P_{\rho 1}$, $P_{\rho 2}$), that is the corresponding range of ($\rho 1$, $\rho 2$), the system will immediately start the fine-tracking of the incremental conductance tracking, use the I_{pv} - V_{pv} curve as the tracking standard, and thus the system can very quickly reach the MPP C (i.e. $\Delta I/\Delta V = -I/V$), corresponding to the MPP C' (i.e. $dP/dV=0$). This technique can not only improve the slow tracking speed of the incremental conductance method, but also ensure the accuracy of the MPPT, and increase the efficiency of the MPPT. FIGS. 2(a)-2(b) respectively show the waveform diagrams of the various tracking routes of the PI-INC MPPT method proposed by the present invention and the INC MPPT method when it is fallen on the right-hand side and the left-hand side of the MPP. As shown in FIG. 2(a), when the PI-INC MPPT method proposed by the present invention is used, and it is fallen on the right-hand side of the MPP, the P_{pv} - V_{pv} curve is used to track firstly, and then the I_{pv} - V_{pv} curve is used when the range of ($\rho 1$, $\rho 2$) is entered. As shown in FIG. 2(b), when the PI-INC MPPT method proposed by the present invention is used, and it is fallen on the left-hand side of the MPP, the P_{pv} - V_{pv} curve is used to track firstly, and then the I_{pv} - V_{pv} curve is used when the range of ($\rho 1$, $\rho 2$) is entered. As for the INC MPPT method, it uses the I_{pv} - V_{pv} curve to track no matter where it falls on.

According to FIG. 1(a), the typical I_{pv} - V_{pv} relationship of a practical photovoltaic cell, neglecting R_{sh} , can be described by

$$I_{pv} = I_{ph} - I_{pvo} \left\{ \exp \left[\frac{q}{AkT} (V_{pv} + I_{pv} R_s) \right] - 1 \right\} \quad (1')$$

and

$$V_{pv} = \frac{AkT}{q} \ln \left(\frac{I_{ph} - I_{pv} + I_{pvo}}{I_{pvo}} \right) - I_{pv} R_s \quad (2)$$

and

$$\frac{dI_{pv}}{dV_{pv}} = -\frac{q}{AkT} I_{pvo} e^{\frac{q}{AkT} (V_{pv} + I_{pv} R_s)} \left(1 + \frac{q}{AkT} R_s I_{pvo} e^{\frac{q}{AkT} (V_{pv} + I_{pv} R_s)} \right)^{-1} \quad (3)$$

where I_{ph} denotes light-generated current, I_{pvo} is dark saturation current, I_{pv} is PV electric current, V_{pv} is PV voltage, R_s is series resistance, A is the non-ideality factor, k is Boltzmann's constant, T is temperature, and q is the electronic charge. The output power from the PV cell can be given by

$$P_{pv} = V_{pv} I_{pv} = I_{pv} \left\{ \frac{AkT}{q} \ln \left(\frac{I_{ph} - I_{pv} + I_{pvo}}{I_{pvo}} \right) - I_{pv} R_s \right\} \quad (4)$$

and

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-continued

$$\frac{dP_{pv}}{dV_{pv}} = I_{pv} + V_{pv} \cdot \frac{dI_{pv}}{dV_{pv}} \quad (5)$$

The MPP in the PV array occurs when

$$\frac{dP_{pv}}{dV_{pv}} = 0 \quad (6)$$

The criteria for the INC MPPT at MPP can then be given from (6),

$$\frac{dI_{pv}}{dV_{pv}} = -\frac{I_{pv}}{V_{pv}} \quad (7)$$

Referring to FIG. 1(b), $dP_{pv}/dV_{pv}=0$ on the P_{pv} - V_{pv} curve is equal to MPP of $dI_{pv}/dV_{pv} = -I_{pv}/V_{pv}$ on the I_{pv} - V_{pv} curve. In difference expression, (7) becomes

$$\frac{\Delta I_{pv}}{\Delta V_{pv}} \approx \frac{dI_{pv}}{dV_{pv}} = -\frac{I_{pv}}{V_{pv}} \quad (8)$$

and (8) can also be represented by

$$\Delta I_{pv} V_{pv} + \Delta V_{pv} I_{pv} = 0 \quad (9)$$

From ΔC as shown via the I_{pv} - V_{pv} curve, the boundaries of the proposed INC MPPT method are,

$$-\rho_1 \frac{I_{pv}}{V_{pv}} > \Delta C > -\rho_2 \frac{I_{pv}}{V_{pv}} \quad (10)$$

for INC tracking along the I_{pv} - V_{pv} curve in CTZ (or TTZ), and

$$\Delta C > -\rho_1 \frac{I_{pv}}{V_{pv}} \quad (11)$$

or

$$\Delta C < -\rho_2 \frac{I_{pv}}{V_{pv}} \quad (12)$$

for the PI tracking along the P_{pv} - V_{pv} curve beyond the CTZ (or TTZ), but in the sense of INC MPPT, it is for INC tracking along the I_{pv} - V_{pv} curve, where the ΔC is defined as

$$\Delta C = \frac{\Delta I_{pv}}{\Delta V_{pv}} \quad (13)$$

where the two ratios ρ_1 and ρ_2 are real numbers and let $\rho_m=1$ at MPP. Equation (13) is negative because the signs of ΔI_{pv} and ΔV_{pv} are always opposite. Accordingly, from (8) and (10),

$$-\rho_1 > \frac{\Delta I_{pv} V_{pv}}{\Delta V_{pv} I_{pv}} > -\rho_2 \quad (14)$$

From (5), by difference approach,

$$\begin{aligned} dP_{pv} &\approx \Delta P_{pv} \\ &= V_{pv}\Delta I_{pv} + I_{pv}\Delta V_{pv} \end{aligned} \quad (15)$$

All increments in (15) are defined as follows.

$$\Delta P = P_{n+1} - P_n \quad (16)$$

$$\Delta V = V_{n+1} - V_n \quad (17)$$

and

$$\Delta I = I_{n+1} - I_n \quad (18)$$

where all subscripts pv are omitted for simplicity in analysis, such that $\Delta P = \Delta P_{pv}$, $\Delta V = \Delta V_{pv}$, and $\Delta I = \Delta I_{pv}$. Related to the definition of the CTZ in (10), a corresponding PTZ is equivalently defined by

$$P_{\rho 1} > \Delta P > P_{\rho 2} \quad (19)$$

for PI-INC MPPT in PTZ (or TTZ), which uses INC tracking toward MPP along the I_{pv} - V_{pv} curve, and

$$\Delta P > P_{\rho 1} \quad (20)$$

or

$$\Delta P < P_{\rho 2} \quad (21)$$

for PI-INC MPPT excluding the PTZ (or TTZ), which uses the PI tracking toward either point $P_{\rho 1}$ or $P_{\rho 2}$ along the P_{pv} - V_{pv} curve. Subsequently, by adding one to all terms in (14) yields

$$1 - \rho_1 > \frac{\Delta V_{n+1}}{\Delta V_{I_{n+1}}} + 1 > 1 - \rho_2 \quad (22)$$

and

$$(1 - \rho_1)\Delta V_{I_{n+1}} > \Delta P > (1 - \rho_2)\Delta V_{I_{n+1}} \quad (23)$$

where ΔV and ΔI have opposite signs and $\rho_2 > \rho_m > \rho_1$ with $\rho_m = 1$. The two power threshold limits in (23) are then defined by

$$P_{\rho 1} = (1 - \rho_1)\Delta V_{I_{n+1}} \quad (24)$$

and

$$P_{\rho 2} = (1 - \rho_2)\Delta V_{I_{n+1}} \quad (25)$$

If $1 - \rho_2 = -(1 - \rho_1)$ is adopted for example, then the values of (24) and (25) are equal and yield

$$P_{\rho 2} = -P_{\rho 1} \quad (26)$$

and from (19),

$$P_{\rho 1} > \Delta P > -P_{\rho 1} \quad (27)$$

A summary of the tracking of PI-INC MPPT is briefly described as follows:

Case I: Tracking in TTZ zone: the priority measure for guiding judgment is ΔC in (10) and the minor for monitoring is ΔP in (19).

(1) The PI-INC MPPT guides the PV converter using INC tracking along the I_{pv} - V_{pv} curve toward MPP.

(2) Once $\Delta C = -I_{n+1}/V_{n+1}$, corresponding to $\Delta P = 0$, the system will exactly operate at MPP that is kept by the PI-INC MPPT using INC tracking along the I_{pv} - V_{pv} curve.

Case II: Tracking beyond the TTZ zone: the priority measure for guiding judgment is ΔP in (19) and the minor for monitoring is ΔC in (10).

(1) If $\Delta P \neq 0$ but $\Delta P > P_{\rho 1}$ in (20), in the left-hand side of TTZ, the PI-INC MPPT guides the PV converter using PI tracking along the P_{pv} - V_{pv} curve toward point $P_{\rho 1}$.

(2) If $\Delta P \neq 0$ but $\Delta P < P_{\rho 2}$ in (21), in the right-hand side of TTZ, the PI-INC MPPT guides the PV converter using PI tracking along the P_{pv} - V_{pv} curve toward point $P_{\rho 2}$.

As shown in FIG. 3(a), it depicts a photovoltaic system according to the preferred embodiment of the present invention, being a photovoltaic DC link converter and including a PI-INC MPPT controller, and the controller uses a constant-frequency variable-duty (CFVD) control, and is guided by a control chart, wherein the control chart includes an I_{pv} - V_{pv} curve and a P_{pv} - V_{pv} curve, a dI_{pv}/dV_{pv} - V_{pv} curve, a dI_{pv}/dV_{pv} - d_B curve, and a P_o - d_B curve (the above-mentioned curves are shown in FIG. 4). Besides, the photovoltaic system further includes a PV array, a boost current converter (BCC), a pulse-width modulation (PWM) driver, and a DC bus, the boost current converter (including an inductor L_B , a switch Q_B and a diode D) is electrically connected to the PV array and the PI-INC MPPT controller, the PWM driver (including two operational amplifiers) is electrically connected to the PI-INC MPPT controller and the boost current converter, the DC bus (including a battery set and a load Z_L) is electrically connected to the boost current converter, and the PI-INC controller is employed to cause the system to engage in an MPPT.

The BCC is duty-controlled by PI-INC MPPT that can provide proper duty period $d_B T_s$ for driving the BCC at MPP according to the insolation level. The duty ratio d_B guided from PI-INC MPPT controls the BCC to draw energy from PV array toward MPP at a constant frequency with a PI coarse-tracking before reaching threshold zone (THZ), and an INC fine-tracking in THZ. The BCC is desirable to operate between BCM and DCM for achieving pulse charge to battery that connects with DC bus. The dynamic states of BCC in BCM and DCM are shown in FIGS. 3(b) and 3(c), respectively. If BCC is used for DC bus survived with a battery, V_B is greater than maximum V_{pv} , and provided that all components are ideal and BCC operates between DCM and BCM as shown in FIGS. 2(b) and 2(c), the peak inductor current i_{L_peak} will exactly release to zero at $t = t^*$.

The peak inductor current i_L of the boost-current-source DC bus (BCS-DCB) in FIGS. 6(b)-(c) can be represented by

$$i_L = \frac{V_{pv}}{L_B} \cdot d_B T_s \quad (28)$$

where L_B is the boost inductor and d_B the duty ratio. The inductor current i_L which is equal to PV current i_{pv} during the energy release time $t \geq d_B T_s$, can be given by

$$\begin{aligned} i_L &= i_L - \frac{V_B - V_{pv}}{L_B} (t - d_B T_s) \\ &= i_{pv} \end{aligned} \quad (29)$$

At $t = t^*$, the inductor current i_L will exactly release to zero, and from (29), yield

$$t^* = \frac{V_B}{V_B - V_{pv}} \cdot d_B T_s \quad (30)$$

Equation (30) is valid for BCS-DCB between DCM and BCM under $V_B > V_{pv}$. When $t' = T_s$, the BCS-DCB is exactly at BCM and the duty ratio $d_{B,BCM}$ can be expressed as

$$d_{B,BCM} = 1 - \frac{V_{pv}}{V_B} \quad (31)$$

and the peak inductor current and peak PV current at BCM will be

$$\begin{aligned} \hat{I}_{L,BCM} &= \frac{V_{pv}}{L_B} \cdot \frac{V_B - V_{pv}}{V_B} T_s \\ &= \hat{I}_{pv,BCM} \end{aligned} \quad (32)$$

At BCM, the boundary duty ratio in (31) and the PV peak current in (32) are dependent on the PV voltage V_{pv} that is subject to the solar insolation, under the DC bus voltage equal to V_B . From (28), we then have average PV current I_{pv} ,

$$I_{pv} = \frac{V_B V_{pv}}{V_B - V_{pv}} \cdot \frac{d_B^2}{2L_B f_s} \quad (33)$$

where $f_s = 1/T_s$. If power efficiency η of the BCS-DCB is considered, the relation of output power P_o and input power P_{pv} is given by,

$$\eta I_{pv} V_{pv} = I_{o,B} V_B \quad (34)$$

where $V_o = V_B$, $P_o = I_{o,B} V_B$. The output current $I_{o,B}$ ($= I_B$) to DC bus from (33) and (34) will be

$$\begin{aligned} I_{o,B} &= I_B \\ &= \frac{\eta V_{pv}^2 d_B^2}{2L_B (V_B - V_{pv}) f_s} \end{aligned} \quad (35)$$

The control-to-output transfer function of the BCS-DCB is then given by

$$\frac{\sqrt{I_{o,B}}}{d_B} = \left(\frac{\eta V_{pv}^2}{2L_B (V_B - V_{pv}) f_s} \right)^{\frac{1}{2}} \quad (36)$$

And

$$P_{o,B} = \frac{\eta V_B V_{pv}^2 d_B^2}{2L_B (V_B - V_{pv}) f_s} \quad (37)$$

Equation (36) presents the control-to-output transfer function, in which the square-root of output current $I_{o,B}$ is proportional to the duty ratio d_B . Moreover, the output power P_o is in proportion to the square of duty ratio d_B . The model of the BCS-DCB associated with the PV array and DC bus from (36) is then shown in FIG. 3(d).

An algorithm of PI-INC MPPT using CFVD is depicted in FIGS. 5(a)-(b). The algorithm is programmed according to the derived formulas (10) and (19), and refers to the control chart as shown in FIG. 4. The outlines of the algorithm are listed in FIGS. 5(a)-(b). In FIG. 5(a), the main program samples the instantaneous information come from the PV array as the new data to be used in the subroutine of

FIG. 5(b). The subroutine uses the data from the main program to calculate the instantaneous PV voltage, current and power firstly, and then uses the standards in formulas (10) and (19) to execute the PI-INC MPPT. The main program provides a direction D_n at the very beginning, it is 1 or 0, to change the duty ratio so as to decrease or increase the PV current respectively. Thus, at the very beginning, a PI fine adjustment or an INC coarse adjustment towards the MPP is engaged in. In this algorithm, a power difference comparison is accomplished by referring to formula (19) and compared with P_{p1} of formula (24) and P_{p2} of formula (25). In other words, via the two power inequalities (20) and (21), the direction of tracking is quite easy to be determined.

Design and Experiment

The algorithm of PI-INC MPPT is executed by Microchip dsPIC33FJ06GS202 according to the guided flowchart in FIGS. 5(a)-(b). Besides, an experimental setup with two PV arrays in series with a maximum power of 250 W, and four lead acid batteries (LABs) each have a specification of 45 AH, is established with the circuit structure as shown in FIG. 3(a). The photovoltaic DC link converter is specified to charge with a positive peak current pulse of 7.2 A for BCC to battery. The control duty ratio BCS-DCB is 0.36 at MPP under insolation 1 kW/m² with the constant frequency set to 40 kHz. FIGS. 6(a)-(b) respectively show the reactions of the photovoltaic DC link converter using the CFVD control, wherein FIG. 6(a) shows the waveform of output current versus duty ratio, and FIG. 6(b) shows the waveform of output power versus duty ratio, in which the solid line shows the results of the simulation, and the dotted line shows the results of the experiment (including three solar insolation, 300 W/m², 600 W/m², and 1 kW/m²). In FIGS. 6(a)-(b), the results of simulation are quite close to the results of the experimental measurement. Thus, the tracking chart (see FIG. 4) of PI-INC MPPT is useful in guiding practical design.

FIG. 7 shows the measured output current $i_{o,B}$ with respect to the gate drive signals of Q_B at a frequency of 40 kHz with duty ratio of 0.36, before they are sent to DC bus with four batteries connected in series, wherein the measured waveforms are the same as those predicted by FIGS. 3(b)-(c).

FIG. 8 compares PI-INC MPPT and INC-MPPT in terms of dynamic tracking behavior for various insolation changes, in which the tracking time responses to MPP are estimated for five kinds of scenarios of insolation change. This comparison reveals that PI INC MPPT has a faster tracking performance than that of INC MPPT over 3-4 times during a large change in insolation.

Embodiments

1. A photovoltaic system with a photovoltaic current (I_{pv}), a photovoltaic voltage (V_{pv}), a photovoltaic power (P_{pv}), a duty cycle (d_B) and an output power (P_o), wherein there is a derivative (dI_{pv}/dV_{pv}) of I_{pv} with respect to V_{pv} , comprising:

- a power-increment-aided incremental-conductance (PI-INC) maximum power point tracking (MPPT) controller guided by a control chart, wherein the control chart includes:
 - an I_{pv} - V_{pv} curve and a P_{pv} - V_{pv} curve;
 - a dI_{pv}/dV_{pv} - V_{pv} curve;
 - a dI_{pv}/dV_{pv} - d_B curve; and
 - a P_o - d_B curve.

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2. A system according to Embodiment 1, wherein the PI-INC MPPT controller uses a constant-frequency variable-duty control.

3. A system according to Embodiment 2 or 3 being one selected from a group consisting of a photovoltaic charger, a photovoltaic DC link converter and a photovoltaic inverter.

4. A system according to anyone of the above-mentioned Embodiments being the photovoltaic DC link converter and further comprising a photovoltaic (PV) array, a boost current converter, a pulse-width modulation (PWM) driver and a DC bus, wherein the boost current converter is electrically connected to the PV array and the PI-INC MPPT controller, the PWM driver is electrically connected to the PI-INC MPPT controller and the boost current converter, the DC bus is electrically connected to the boost current converter, and the PI-INC MPPT controller is used to cause the system to perform an MPPT.

5. A system according to anyone of the above-mentioned embodiments, wherein when a specific conductance derivative ratio on the I_{pv} - V_{pv} curve is located in a threshold tracking zone having a minimum value larger than a first conductance derivative ratio and a maximum value smaller than a second conductance derivative ratio, the controller uses the I_{pv} - V_{pv} curve to perform an INC fine tracking, when the specific conductance derivative ratio is located outside the threshold tracking zone, the controller uses the P_{pv} - V_{pv} curve to perform a PI coarse tracking, and when the first conductance derivative ratio is ρ_1 and the second conductance derivative ratio is ρ_2 ,

$$-\rho_1 > \frac{\Delta I_{pv} V_{pv}}{\Delta V_{pv} I_{pv}} > -\rho_2,$$

where V_{pv} is an output voltage of the PV array, I_{pv} is an output current of the PV array, ΔI_{pv} is a change of the I_{pv} , and ΔV_{pv} is a change of the V_{pv} .

6. A photovoltaic system, comprising:

a controller including a power-increment (PI) module to be used to determine whether a specific conductance derivative ratio enters a threshold tracking zone.

7. A photovoltaic system according to Embodiment 6, wherein the controller further includes an incremental-conductance (INC) module to be used to operate the controller when the specific conductance derivative ratio enters the threshold tracking zone.

8. A photovoltaic system according to Embodiment 6 or 7 further comprising a photovoltaic current (I_{pv}), a photovoltaic voltage (V_{pv}) and a photovoltaic power (P_{pv}), wherein the PI module includes a P_{pv} - V_{pv} curve, the INC module includes an I_{pv} - V_{pv} curve, and the controller is guided by the P_{pv} - V_{pv} curve and the I_{pv} - V_{pv} curve such that the photovoltaic system is engaged in an MPPT.

9. A system according to anyone of the above-mentioned Embodiment being one selected from a group consisting of a photovoltaic charger, a photovoltaic DC link converter and a photovoltaic inverter.

10. A system according to anyone of the above-mentioned embodiments being the photovoltaic DC link converter and further comprising a photovoltaic (PV) array, a boost current converter, a pulse-width modulation (PWM) driver and a DC bus, wherein the controller is a PI-INC MPPT controller, the boost current converter is electrically connected to the PV array and the PI-INC MPPT controller, the PWM driver is electrically connected to the PI-INC MPPT controller and the boost current converter, the DC bus is electrically

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connected to the boost current converter, and the PI-INC MPPT controller is used to cause the system to engage in an MPPT.

11. A system according to anyone of the above-mentioned embodiments, wherein when the specific conductance derivative ratio on the I_{pv} - V_{pv} curve is located in the threshold tracking zone having a minimum value larger than a first conductance derivative ratio and a maximum value smaller than a second conductance derivative ratio, the controller uses the I_{pv} - V_{pv} curve to engage in an INC fine tracking, when the specific conductance derivative ratio is located outside the threshold tracking zone, the controller uses the P_{pv} - V_{pv} curve to engage in a PI coarse tracking, and when the first conductance derivative ratio is ρ_1 and the second conductance derivative ratio is ρ_2 ,

$$-\rho_1 > \frac{\Delta I_{pv} V_{pv}}{\Delta V_{pv} I_{pv}} > -\rho_2,$$

where V_{pv} is an output voltage of the PV array, I_{pv} is an output current of the PV array, ΔI_{pv} is a change of the I_{pv} , and ΔV_{pv} is a change of the V_{pv} .

12. A system according to anyone of the above-mentioned embodiments further comprising a derivative (dI_{pv}/dV_{pv}) of I_{pv} with respect to V_{pv} , a duty cycle (d_B) and an output power (P_o), wherein the controller is further guided by a dI_{pv}/dV_{pv} - V_{pv} curve, a dI_{pv}/dV_{pv} - d_B curve, and a P_o - d_B curve.

13. A method for operating a controller of a photovoltaic system, comprising a step of: providing a power-increment (PI) module to be used to determine whether a specific conductance derivative ratio enters a threshold tracking zone.

14. A method according to Embodiment 13, wherein the controller further includes an incremental-conductance (INC) module to be used to operate the controller when the specific conductance derivative ratio enters the threshold tracking zone.

15. A method according to Embodiment 13 or 14, wherein the photovoltaic system further comprises a photovoltaic current (I_{pv}), a photovoltaic voltage (V_{pv}) and a photovoltaic power (P_{pv}), the PI module includes a P_{pv} - V_{pv} curve, the INC module includes an I_{pv} - V_{pv} curve, the threshold tracking zone has a minimum value larger than a first conductance derivative ratio and a maximum value smaller than a second conductance derivative ratio, and the I_{pv} - V_{pv} curve, the P_{pv} - V_{pv} curve and the threshold tracking zone are provided to guide the controller, the method further comprising steps of:

a) causing the controller to use a constant-frequency variable-duty control to engage in an MPPT;

b) causing the controller to use the I_{pv} - V_{pv} curve to engage in an INC fine tracking when the specific conductance derivative ratio is located in the threshold tracking zone; and

c) causing the controller to use the P_{pv} - V_{pv} curve to engage in a PI coarse tracking when the specific conductance derivative ratio is located outside the threshold tracking zone.

16. A method according to anyone of the above-mentioned embodiments, wherein the photovoltaic system further comprises a photovoltaic (PV) array, and when the first conductance derivative ratio is ρ_1 and the second conductance derivative ratio is ρ_2 ,

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$$-\rho_1 > \frac{\Delta I_{pv} V_{pv}}{\Delta V_{pv} I_{pv}} > -\rho_2,$$

where V_{pv} is an output voltage of the PV array, I_{pv} is an output current of the PV array, ΔI_{pv} is a change of the output current of the PV array I_{pv} , and ΔV_{pv} is a change of the output voltage V_{pv} of the PV array.

17. A method according to anyone of the above-mentioned embodiments, wherein the step b) further comprises sub-steps of:

when the conductance derivative ratio is smaller than ρ_1 , causing the V_{pv} to increase a positive value of ΔV_{pv} via the controller so as to get a change ΔP_{pv} of an output power P_{pv} of the PV array via the P_{pv} - V_{pv} curve and to stop when $\Delta P_{pv}/\Delta V_{pv} = dP_{pv}/dV_{pv} = 0$, where dP_{pv}/dV_{pv} is a derivative of P_{pv} with respect to V_{pv} ;

when the conductance derivative ratio is larger than ρ_2 , causing the V_{pv} to decrease the positive value of ΔV_{pv} via the controller so as to get the change ΔP_{pv} of the output power P_{pv} of the PV array via the P_{pv} - V_{pv} curve and to stop when $\Delta P_{pv}/\Delta V_{pv} = dP_{pv}/dV_{pv} = 0$;

when $\rho_1 \leq$ the conductance derivative ratio $\leq \rho_2$ and $\Delta I_{pv}/\Delta V_{pv} > -I_{pv}/V_{pv}$, causing the V_{pv} to increase the positive value of ΔV_{pv} via the controller so as to get a change ΔI_{pv} of the output current I_{pv} of the PV array via the I_{pv} - V_{pv} curve and to stop when $\Delta I_{pv}/\Delta V_{pv} = -I_{pv}/V_{pv}$; and

when $\rho_1 \leq$ the conductance derivative ratio $\leq \rho_2$ and $\Delta I_{pv}/\Delta V_{pv} < -I_{pv}/V_{pv}$, causing the V_{pv} to decrease the positive value of ΔV_{pv} via the controller so as to get the change ΔI_{pv} of the output current I_{pv} of the PV array via the I_{pv} - V_{pv} curve and to stop when $\Delta I_{pv}/\Delta V_{pv} = -I_{pv}/V_{pv}$.

According to the aforementioned descriptions, the present invention provides a photovoltaic system having a power-increment-aided incremental-conductance maximum power point tracking controller using a constant-frequency variable-duty control. This technique includes PI-MPPT and INC-MPPT, and sets up a threshold tracking zone in the area with obvious changes on the I_{pv} - V_{pv} curve around point C. If the power increment falls into the threshold tracking zone, the system enters the INC fine tracking and uses the I_{pv} - V_{pv} curve as a tracking standard. On the contrary, if the power increment falls outside the threshold tracking zone, the system enters the PI coarse tracking and uses the P_{pv} - V_{pv} curve as a tracking standard. The proposed photovoltaic system has a relatively quick response and a relatively better output efficiency of the maximum power when engaged in the MPPT so as to possess the non-obviousness and the novelty.

While the present invention has been described in terms of what are presently considered to be the most practical and preferred embodiments, it is to be understood that the present invention need not be restricted to the disclosed embodiments. On the contrary, it is intended to cover various modifications and similar arrangements included within the spirit and scope of the appended claims which are to be accorded with the broadest interpretation so as to encompass all such modifications and similar structures. Therefore, the above description and illustration should not be taken as limiting the scope of the present invention which is defined by the appended claims.

What is claimed is:

1. A photovoltaic system, comprising:

a controller including a power-increment (PI) module to be used to determine whether a specific conductance derivative ratio enters a threshold tracking zone, and an

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incremental-conductance (INC) module to be used to operate the controller when the specific conductance derivative ratio enters the threshold tracking zone;

a photovoltaic current (I_{pv});

a photovoltaic voltage (V_{pv}); and

a photovoltaic power (P_{pv}), wherein the PI module includes a P_{pv} - V_{pv} curve, the INC module includes an I_{pv} - V_{pv} curve, the controller is guided by the P_{pv} - V_{pv} curve and the I_{pv} - V_{pv} curve such that the photovoltaic system is engaged in a maximum power point tracking (MPPT), when the specific conductance derivative ratio on the I_{pv} - V_{pv} curve is located in the threshold tracking zone having a minimum value larger than a first conductance derivative ratio and a maximum value smaller than a second conductance derivative ratio, the controller uses the I_{pv} - V_{pv} curve to engage in an INC fine tracking, when the specific conductance derivative ratio is located outside the threshold tracking zone, the controller uses the P_{pv} - V_{pv} curve to engage in a PI coarse tracking, and when the first conductance derivative ratio is ρ_1 and the second conductance derivative ratio is ρ_2 ,

$$-\rho_1 > \frac{\Delta I_{pv} V_{pv}}{\Delta V_{pv} I_{pv}} > -\rho_2,$$

where V_{pv} is an output voltage of the PV array, I_{pv} is an output current of the PV array, ΔI_{pv} is a change of the I_{pv} , and ΔV_{pv} is a change of the V_{pv} .

2. A system according to claim 1 wherein the system is selected from a group consisting of a photovoltaic charger, a photovoltaic DC link converter and a photovoltaic inverter.

3. A system according to claim 2 wherein the photovoltaic DC link converter further comprises a photovoltaic (PV) array, a boost current converter, a pulse-width modulation (PWM) driver and a DC bus, wherein the controller is a power-increment-aided incremental-conductance (PI-INC) MPPT controller, the boost current converter is electrically connected to the PV array and the PI-INC MPPT controller, the PWM driver is electrically connected to the PI-INC MPPT controller and the boost current converter, the DC bus is electrically connected to the boost current converter, and the PI-INC MPPT controller is used to cause the system to engage in an MPPT.

4. A system according to claim 1 further comprising a derivative (dI_{pv}/dV_{pv}) of I_{pv} with respect to V_{pv} , a duty cycle (d_b) and an output power (P_o), wherein the controller is further guided by a dI_{pv}/dV_{pv} - V_{pv} curve, a dI_{pv}/dV_{pv} - d_b curve, and a P_o - d_b curve.

5. A method for operating a controller of a photovoltaic system, comprising:

a) providing a power-increment (PI) module to be used to determine whether a specific conductance derivative ratio enters a threshold tracking zone, wherein the controller further includes an incremental-conductance (INC) module to be used to operate the controller when the specific conductance derivative ratio enters the threshold tracking zone, the photovoltaic system further comprises a photovoltaic current (I_{pv}), a photovoltaic voltage (V_{pv}) and a photovoltaic power (P_{pv}), the PI module includes a P_{pv} - V_{pv} curve, the INC module includes an I_{pv} - V_{pv} curve, the threshold tracking zone has a minimum value larger than a first conductance derivative ratio and a maximum value smaller than a second conductance derivative ratio, and

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- the I_{pv}-V_{pv} curve, the P_{pv}-V_{pv} curve and the threshold tracking zone are provided to guide the controller;
- b) causing the controller to use a constant-frequency variable-duty control to engage in a maximum power point tracking (MPPT);
- c) causing the controller to use the I_{pv}-V_{pv} curve to engage in an INC fine tracking when the specific conductance derivative ratio is located in the threshold tracking zone; and
- d) causing the controller to use the P_{pv}-V_{pv} curve to engage in a PI coarse tracking when the specific conductance derivative ratio is located outside the threshold tracking zone.
6. A method according to claim 5, wherein the photovoltaic system further comprises a photovoltaic (PV) array, and when the first conductance derivative ratio is ρ_1 and the second conductance derivative ratio is ρ_2 ,

$$-\rho_1 > \frac{\Delta I_{pv} V_{pv}}{\Delta V_{pv} I_{pv}} > -\rho_2,$$

where V_{pv} is an output voltage of the PV array, I_{pv} is an output current of the PV array, ΔI_{pv} is a change of the output current of the PV array I_{pv}, and ΔV_{pv} is a change of the output voltage V_{pv} of the PV array.

7. A method according to claim 6, wherein the step c) further comprises sub-steps of:

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- when the specific conductance derivative ratio is smaller than ρ_1 , causing the V_{pv} to increase a positive value of ΔV_{pv} via the controller so as to get a change ΔP_{pv} of an output power P_{pv} of the PV array via the P_{pv}-V_{pv} curve and to stop when $\Delta P_{pv}/\Delta V_{pv} \approx dP_{pv}/dV_{pv} = 0$, where dP_{pv}/dV_{pv} is a derivative of P_{pv} with respect to V_{pv};
- when the specific conductance derivative ratio is larger than ρ_2 , causing the V_{pv} to decrease the positive value of ΔV_{pv} via the controller so as to get the change ΔP_{pv} of the output power P_{pv} of the PV array via the P_{pv}-V_{pv} curve and to stop when $\Delta P_{pv}/\Delta V_{pv} \approx dP_{pv}/dV_{pv} = 0$;
- when $\rho_1 \leq$ the specific conductance derivative ratio $\leq \rho_2$ and $\Delta I_{pv}/\Delta V_{pv} > -I_{pv}/V_{pv}$, causing the V_{pv} to increase the positive value of ΔV_{pv} via the controller so as to get a change ΔI_{pv} of the output current I_{pv} of the PV array via the I_{pv}-V_{pv} curve and to stop when $\Delta I_{pv}/\Delta V_{pv} = -I_{pv}/V_{pv}$; and
- when $\rho_1 \leq$ the specific conductance derivative ratio $\leq \rho_2$ and $\Delta I_{pv}/\Delta V_{pv} < -I_{pv}/V_{pv}$, causing the V_{pv} to decrease the positive value of ΔV_{pv} via the controller so as to get the change ΔI_{pv} of the output current I_{pv} of the PV array via the I_{pv}-V_{pv} curve and to stop when $\Delta I_{pv}/\Delta V_{pv} = -I_{pv}/V_{pv}$.

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